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TEST OF PRODUCTION OF ^{198}Au RADIOISOTOPE BY MEANS OF TYPICAL MEDICAL LINEAR ACCELERATORS USED IN TELERADIOTHERAPY*

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The test of production of the ^{198}Au radioisotope by means of Varian medical linear accelerators used in teleradiotherapy was carried out. The targets made of the natural gold (100% of the ^{197}Au isotope) were irradiated with high-energy therapeutic 20 MV X-ray beam. ^{198}Au was produced in the simple capture reaction $^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}$. The obtained specific activities in the saturation state are relatively low, not exceeding the value of 510.4 kBq/g, because only the high-energy part of the spectrum of 20 MV X-ray beam covers the energy range of the neutron production cross section. Low activity of the ^{198}Au radioisotope produced by medical linear accelerators makes this technique not suitable for a massive production of ^{198}Au for nuclear medicine, but the produced amount of ^{198}Au is sufficient for laboratory tests of new drugs for possible clinical applications.

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1. Introduction

The characteristics of ^{198}Au — beta emission of 0.96 MeV (98.6%) and 0.412 MeV (95.5%) of gamma radiation [1] — opens many interesting therapeutic possibilities. In fact, ^{198}Au has been widely used to treat the uterus, bladder, cervix, prostate, melanoma, breast, skin and other cancers. The ^{198}Au radioisotope with a high specific activity can be easily produced in

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the simple capture reaction $^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}$ in a nuclear reactor [1]. However, in this work, its production with medical linear accelerators is considered. In our previous paper [1], we demonstrated the technical aspects of the $^{99}\mathrm{Mo}/^{99m}\mathrm{Tc}$ complex production with the use of medical liniacs. In the current work, the 20 MV X-ray therapeutic beam generated by the Clinac TrueBeam linac installed at the Maria Skłodowska-Curie Memorial Cancer Centre and Institute of Oncology in Gliwice (Poland) was applied. Such high-energy photon therapeutic beams induce photonuclear reactions (γ, n) in which neutrons are emitted with a wide spectrum of energies [2–5]. The X-ray beam energy and the produced slowed down neutron fluence are found to be correlated [6–8]. The photonuclear cross section has a resonance character. Its maximum value depends on an atomic number and it is in the range from several millibarns for light nuclei to several hundred millibarns for heavy nuclei. Moreover, the maximum photonuclear cross section corresponds to gamma energy of about 22 MeV for light nuclei and about 12 MeV as the atomic number increases. The energy threshold of the photonuclear reactions is about 8 MeV for most isotopes.

2. Materials and methods

The only stable natural gold isotope $^{197}\mathrm{Au}$ was used as a target material for activation. The gold targets of the 0.5 cm × 0.5 cm × 0.1 mm were mounted on the accelerator window within the therapeutic 20 MV X-ray beam path as well as on the walls of the treatment room. In such locations the gold target is in the neutron field produced during 20 MV X-ray beam emission. The slowed down neutron fluence in the TrueBeam linac accelerator room is almost constant, as reveals from our earlier studies [8]. The cross section of the $^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}$ reaction equals 98.5 barn for thermal neutrons [9]. Moreover, this reaction is characterized by the high resonance

TABLE I

The obtained specific activities of the gold targets in the saturation state A_s with the percentage uncertainties below 1% for various irradiation conditions (ic, the first column). Irradiation fields were determined in a horizontal plane perpendicular to the main axis of the used therapeutic 20 MV X-ray beam at 100 cm from the middle of the target converting electrons into X-rays.

ic	Location of target	Irradiation field	As [kBq/g]
1	bottom of accelerator head	40 cm × 40 cm	97.7
2	wall	3 cm × 3 cm	96.6
3	wall	40 cm × 40 cm	82.2
4	bottom of accelerator head	3 cm × 3 cm	145.0
5	surface of lead block	40 cm × 40 cm	510.4

of 32900 barns at 4.9 eV and several smaller resonances in the epithermal energy range. The resonance activation integral is 1558 barns [10]. The activities of the activated targets were determined from the gamma-ray decay spectra of the produced radioisotope ^{198}Au. The spectra were acquired using two Ge(Li) semiconductor detectors. The energy and efficiency calibration of these detectors was carried out with the use of the commercial sources of ^{152}Eu and ^{133}Ba. The activation of the gold targets was performed for various irradiation conditions (Table I). In one case, the irradiation conditions were modified by adding a system consisting of 5 cm $\times$ 5 cm $\times$ 5 cm blocks of lead located on the PMMA phantom. In such set, lead was an additional source of neutrons, whereas the PMMA material acted as a neutron moderator.

3. Results and discussion

The exemplary spectra of ^{198}Au radioisotope decay are presented in figure 1. In the case of the outside beam target activation, a peak at 411.8 keV dominates in the spectrum (Fig. 1 (a)), whereas for the targets activated inside the beam the decay lines seen at 333.0 keV, 355.7 keV and 426.1 keV correspond to the photons emitted in the decay of ^{196}Au, which itself originates from the photonuclear reaction ^{197}Au$(\gamma, n)^{196}$Au (Fig. 1 (b)). The properties of this radionuclide — its decay photon energies as well as its half-live $T_{1/2} = 6.183$ d — make it very interesting for use in nuclear medicine. Unfortunately, at present, ^{196}Au has not been discovered for medical use yet. We plan to describe the details of the ^{196}Au production by means of a high-energy therapeutic beam from a medical linac in our future paper. The saturation specific activities obtained under various irradiation conditions differ markedly (Table I). In general, the activities of gold targets are greater for the inside-beam activation and for the small radiation filed. Application of the lead-PMMA system increasing a slowed down neutron field led to higher activities. The saturation curve for the case with the obtained maximum saturation activity is shown in figure 2. Due to a relatively long

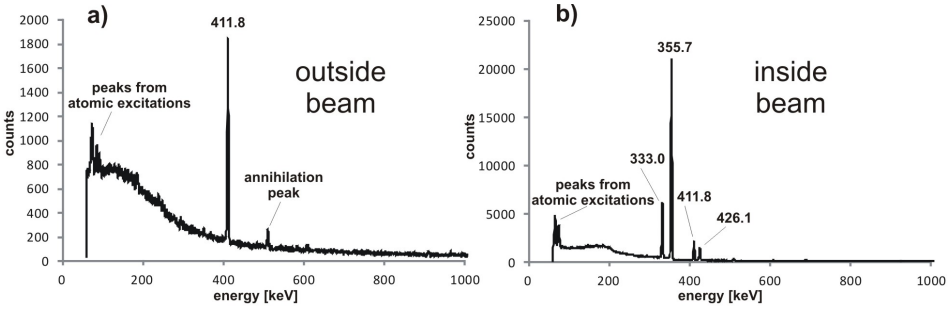

Fig. 1. Spectra of the produced radioisotopes of gold.

half-live of ^{198}Au decay ($T_{1/2}$ = 2.695 d), the time needed for reaching the activity saturation — of about 400 hours — is too long from the practical point of view. Thus, it is necessary to increase a slowed down neutron field significantly. It can be achieved by the appropriate optimization of a configuration of the lead-PMMA shielding blocks placed inside the beam.

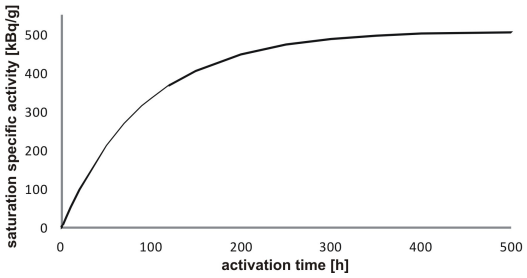

Fig. 2. The saturation curve for the activated gold target under the irradiation conditions with the use of the lead-PMMA system. This is the theoretical curve determined on the base of the experimental parameters.

4. Conclusions

The maximum activity of ^{198}Au generated during operation of medical linear accelerators is too low for this radioisotope to be used in nuclear medicine applications. However, the produced amount of ^{198}Au is sufficient to make use of this radionuclide in laboratory tests of new drugs for potential clinical applications. Moreover, the ^{198}Au activity can be easy increased, if necessary, by increasing a neutron production in photonuclear reactions induced by a therapeutic X-ray beam.

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